NASA-CR-203014

NAGW-2627
IN-92-CR
004 886

Prepared for the GEM Workshop on the Tail and Substorms, Snowmass, 29 June – 1 July 1994

The Stability of Sunward Convection: A Triggering and Operative Mechanism for Substorms

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Abstract

In the 30 years since the substorm was first recognized as a distinct phenomenon, identification of the mechanism responsible for triggering the magnetospheric substorm has eluded the space physics community. In this paper, we wish to set forth the fundamental theoretical/physical context in which the substorm should be viewed. This is the context of M-I coupled convection and the compression of magnetospheric plasma. Within this context we argue that the process of substorm expansion is one in which a "triggering" and an "operative" mechanism need be distinguished. While we view the operative mechanism as near-Earth reconnection, we suggest a modified ballooning scenerio, involving a critical role for M-I coupling in the stability of the magnetospheric configuration, as a mechanism for triggering onset of the substorm expansion phase.

Introduction

The fundamental context in which to attempt to understand the occurrence of substorms is the magnetospheric convection cycle and the effects of flux-tube compression. The magnetospheric convection cycle and its coupling with the ionosphere is apparent in the ionospheric electric field pattern and field-aligned currents flowing between ionosphere and magnetosphere. The cusp/mantle currents evidence the direct interaction of the solar wind/IMF with the magnetosphere. The dayside region-1 currents connect to the LLBL, representing the low-latitude magnetosheath-magnetosphere interface. A portion of the incident solar-wind plasma and magnetic flux enters the magnetosphere and drives transport of this magnetic flux and plasma of both solar-wind and ionospheric origin through the magnetosphere. The high-latitude portion of the nightside region-1 and region-0 currents flow in the PSBL and are associated with the transport of plasma and magnetic flux into the closed-field-line plasma sheet [*Atkinson*, 1992; *Burke et al.*, 1994]. The Harang system, i.e., that portion of the nightside (upward) region-1 current located between the PSBL and region 2, which maps to the near-Earth and middle plasma sheet, results from the different drift paths of ions and electrons and serves to keep momentum flow directed earthward and toward the day side. (See *Atkinson* [1984] and *Erickson et al.* [1991].) The region-2 field-aligned currents (shielding currents) provide for deflection of plasma and magnetic flux, transported earthward in the nightside plasma sheet, around the inner (corotating) magnetosphere and toward the day side to complete the convection cycle [e.g., *Harel et al.*, 1981].

The PBI Problem for Convection

During periods of southward IMF, the return rate of magnetic flux in the plasma sheet usually lags the dayside merging rate because of flux-tube compression [*Erickson and Wolf*, 1980]. As plasma-sheet flux tubes shorten during their earthward transport, their plasma pressure would increase much more than the confining lobe magnetic pressure, if the confining lobe magnetic pressure were not allowed to increase with time. This is the so-called "pressure-balance inconsistency" (PBI) problem. A consequence is that the return rate of magnetic flux transport to the day side usually lags the dayside merging rate, and magnetic flux piles-up in the lobes to provide an increasing confinement pressure for plasma-sheet flux tubes as they convect earthward [*Erickson*, 1992]. (As will be discussed below, flux-tube compression also provides for the large-scale stability of the magnetospheric configuration.) There are three exceptions to this usual state of affairs.

First, during periods of northward IMF the nightside reconnection rate and rate of earthward transport can exceed the dayside merging rate. Over several hours the magnetosphere can relax toward a closed-field-line configuration. Second, during extended periods of steady, southward IMF, the magnetosphere can enter a steady convection state in which the dayside merging rate and nightside reconnection rate are balanced. This is known as a "steady magnetospheric convection" (SMC) event. Theoretically, the PBI problem can be avoided in highly-stretched configurations which contain a deep, near-Earth, local minimum in equatorial magnetic field strength. The B_{eq}-minimum permits plasma-sheet flux tubes to convect earthward without substantial decrease in their volumes, thereby permitting a plasma-sheet pressure scalelength matching that of the lobe pressure. Theoretical steady-state configurations were constructed by *Hau* [1991]. Recently, *Sergeev et al.* [1993] have observationally inferred a magnetospheric configuration during an SMC event consistent with the Hau steady-state model.

The last exception to the usual state of affairs is the magnetospheric substorm. In this context, the magnetospheric substorm is the process in which pressure-bearing ions are released from the midnight sector; plasma-sheet flux tubes are transported rapidly earthward and toward the day side to complete the convection cycle. The release of ions from midnight-sector flux tubes causes these flux tubes to contain less cross-tail drifting plasma than flux tubes nearer the flanks. This, combined with shear as depleted flux tubes rapidly move earthward, requires the substorm current wedge of region-1 sense to maintain charge conservation and quasi-neutrality. M-I coupling via this field-aligned current wedge provides for the enhanced electric field, i.e., enhanced transport within the wedge. The energy stored in the forms of plasma and magnetic flux in the tail during the preceding growth phase, i.e., the usual state of affairs described earlier, is released via rapid transport of depleted plasma-sheet flux tubes toward the day side, injection into the ring current, energy deposition into the ionosphere, and the release of excess plasma within a plasmoid.

It should be noted that without the escape of plasma from flux tubes which close through Earth's main field, the PBI problem remains for those flux tubes. Earthward transport is retarded owing to compression of plasma in those flux tubes as their volumes shrink. If rapid return transport of more than merely the near-Earth, closed magnetic flux is to be involved in the substorm, then formation of a near-Earth X-line and plasmoid escape seems to be an essential requirement for substorm expansion. Note the approximate one-to-one correspondence between observation of plasmoids or travelling compression regions and substorm onsets [*Moldwin and Hughes*, 1993]. (For the purposes of this discussion, "near-Earth" refers to that portion of the plasma sheet out to roughly $25R_E$ on the night side.)

A description similar to the PBI description of the problem imposed on the transport of magnetic flux in the return leg of the magnetospheric convection cycle is the "β-problem" described by *Atkinson* [1994]. We should also mention a fourth exception to the usual state of affairs discussed above, namely, bursty bulk flows (BBFs) [*Angelopoulos et al.*, 1992; *Pontius and Wolf*, 1990; *Chen and Wolf*, 1993]. While the physics of BBF transport is like that of flux tubes within the substorm current wedge, there appears to be sufficient disconnect between BBFs and substorms (location of source, scale, etc.) that, for convenience, we will not discuss them here. The role of BBFs in the magnetospheric convection cycle is an active and important area of investigation.

Stability of Sunward Convection

The power involved, the exponential behavior of the electrojets [*Weimer*, 1992], the scale of the magnetospheric and ionospheric disruptions, and the discussion above strongly suggest that the magnetospheric substorm involves the large-scale stability of magnetospheric configuration and the release of stored energy. During ICS-1 held at Kiruna, we presented results of MHD stability analysis of self-consistent, two-dimensional, magnetospheric convection sequences [*Erickson and Heinemann*, 1992]. The results are consistent with those of *Schindler* [1974] and coworkers. Whereas Schindler and coworkers investigated the stability of asymptotic tail equilibria, our analysis was performed using magnetospheric equilibria which contain the inner-edge region of the plasma sheet. The basic result is that the magnetosphere is stable to compressional fluctuations, i.e., fluctuations in which $\delta P/P \propto -\gamma(\delta V/V)$, where $V = \int ds/B$ is the flux-tube volume and $\gamma = 5/3$. If the plasma sheet flares (thickness increases with downtail distance), then the magnetosphere is unstable to isobaric fluctuations, confirming the results of Schindler and coworkers. In addition, even if the plasma sheet does not flare, the magnetosphere is unstable to isobaric fluctuations if the plasma sheet possesses a local minimum in equatorial magnetic field strength. In Figure 1 the results of the stability analysis are summarized. The fundamental normal mode, namely, inward/outward oscillation of plasma-sheet flux tubes, was found to be most unstable under isobaric constraints. (This normal mode is one of the degrees of freedom in the Faraday-loop model of *Klimas et al.* [1992].) Note, not only does the plasma sheet flare, but it appears that a local minimum forms in equatorial magnetic field strength, evidenced both by the observed thinning of the near-Earth current sheet [e.g., *Pulkkinen et al.*, 1992] during the growth phase and the thin near-Earth current sheet observed and equatorial field minimum inferred by *Sergeev et al.* [1993] during an SMC. Either condition, the field minimum or flaring, is sufficient for instability of the large-scale configuration, if it were not for flux-tube compression.

The central issue concerning onset of substorm expansion, and the answer which has eluded us for 30 years, is identification of the mechanism or mechanisms by which the magnetospheric state changes from the stable, quasi-static, compressional branch to the unstable (near) isobaric branch shown in Figure 1, whereby stored energy can be released to drive the dynamic substorm expansion phase. Whether viewed within the context of the PBI problem (excepting SMCs) or viewed within the large-scale stability of the magnetospheric configuration, the central problem is the same. For rapid return transport of substantial magnetic flux to proceed, i.e., the magnetospheric substorm, pressure-bearing ions must escape from nightside flux tubes closed through Earth's main field. This points to reconnection as the operative mechanism of substorm expansion.

M-I coupling will prevent substantial, substained ion loss if flux tubes are not opened. Suppose ions try to drift westward out of closed flux tubes whether in the "wall" description of *Ashour-Abdalla et al.* [1992] or if the current sheet were so thin that ions demagnetize. The result of M-I coupling in such cases is the same as described in connection with the Harang discontinuity [*Erickson et al.*, 1991]. Current continuity would require upward field-aligned current into (and electron precipitation from) the loss region. Ionospheric current closure would result in modification of the convection electric field such as to oppose the separation of the charge species. Furthermore, the sense of the field-aligned current is opposite that of the substorm current wedge. Also, as discussed in the next section, a local response, namely the cross-field current instabilities described by *Lui et al.* [1990, 1991, 1993], will probably prevent sustained demagnetization of ions in the absence of an external driver.

Thus, as noted earlier, reconnection appears to be the operative mechanism required for substorm expansion to proceed. Without near-Earth X-line formation, a pseudobreakup or even what some might call a small substorm can proceed. However, it appears that the energy release and magnetic flux transport of what all would call a substorm expansion requires that a near-Earth X-line forms. While reconnection appears to be the operative mechanism of substorm expansion, what triggers onset of substorm expansion?

Suggested Trigger Mechanisms

The classes of mechanisms suggested as responsible for triggering substorm onset include M-I coupling, tearing, current disruption, ballooning, and boundary-layer mechanisms. A lengthy discussion of these mechanisms is provided by *Erickson* [1994 – paper 1]. Here, we briefly summarize.

While the boundary layers cannot in the last analysis be ignored when attempting to resolve all the questions concerning substorm occurrence, in light of the Kiruna conjecture [*Kennel*, 1992] and the discussions above, we can defer discussion of their role in substorm onset. M-I coupling mechanisms such as those suggested by, e.g., *Chao et al.* [1977], *Haerendel* [1992], or *Zhu and Kan* [1990] are perhaps best considered as auroral intensification models like those of *Heppner et al.* [1967], *Coroniti and Kennel* [1972] and *Rothwell et al.* [1991]. The "unloading instability" suggested by *Kan* [1993] might not be more than the mechanism of auroral fading discussed by *Pellinen and Heikkila* [1978]. (See paper 1 for a detailed discussion.) None of these models address the central issue concerning the onset of substorm expansion discussed above. Via M-I coupling locally-intense convection electric fields can develop, especially as parallel potential drops turn on. Near the inner-edge region of the plasma sheet, flux tubes can undergo fast azimuthal convection since their volumes do not have to undergo substantial change and plasma compression is not a problem. However, as flux tubes downtail attempt to follow, (excepting SMC events) their volumes will shrink and the plasma will be compressed; the PBI problem remains, and convection will be slowed. This is not to say that M-I coupling plays no role in substorm onset; it probably plays a critical role. Its role, however, needs to be examined within the context of the large-scale stability of the magnetosphere.

Current disruption, specifically the cross-field current instability (CFCI) proposed by *Lui et al.* [1990, 1991, 1993], and tearing [e.g., *Schindler*, 1974] do involve release of plasma from flux tubes. As noted earlier, reconnection is probably the operative mechanism of substorm expansion. However, when regarding current disruption or tearing as triggering mechanisms for onset, these too appear to be plagued by compressional stabilization.

Theoretically, the ion tearing mode is stabilized by electron compressibility which slows ion diffusion needed for the mode to grow. Recent reports tend to support this state of affairs. *Winske and Hesse* [1994] reported on hybrid simulations using a realistic ion-to-electron mass ratio. Their findings tend to confirm the view expressed by, e.g., *Wang and Bhattacharjee* [1993] that the magnetotail is stable to ion tearing. Also, *Brittnacher et al.* [1994] have re-examined use of the energy principle as applied to the tearing instability as used by *Pellat et al.* [1991], *Kuznetsova and Zelenyi* [1991] and others. Their conclusion agrees with that of Pellat et al. that stabilization of the ion tearing mode cannot be removed by electron pitch-angle diffusion. It has been suggested that a magnetic shear component can lengthen electron bounce times sufficiently to allow ion tearing to proceed effectively. Moreover, there are effects of three-dimensionality and M-I coupling which have not been addressed that might provide a path for tearing to proceed. (See paper 1 and references therein for a discussion of these issues.) At present, however, it appears that the presence of a normal magnetic field component stabilizes tearing.

The mathematical analysis of the CFCI is performed in the local approximation. Note that in the local approximation only current density is addressed; to determine the effect on total current in the plasma sheet and magnetic flux transport, the CFCI must be considered in a non-local context. If one takes care to conserve energy, without regard to the surrounding environment, one finds that the CFCI results in an increase of B and the earthward $\mathbf{j}\times\mathbf{B}$ force as well as plasma pressure. The energy is provided by the streaming energy of the previously demagnetized ions. There is something uncomfortable with respect to the second law of thermodynamics about the notion of gyromotion, associated with the entropy of the plasma, being converted to ordered streaming in the absence of an external driver. The CFCI might be viewed as Nature's way to avoid this situation. As the current sheet gradually thins in the growth phase to the point where ions can demagnetize, the CFCI scatters and ions remagnetize.

Consider the CFCI operating within some larger radial extent of the current sheet. Away from the earthward edge of the disruption region we do not know what happens to the pressure gradient, nor for that matter the $\mathbf{j}\times\mathbf{B}$ force, as we leave the local approximation. We can attempt to analyze the outcome. At the earthward edge of the disruption region, a flux tube will see an unbalanced earthward $\mathbf{j}\times\mathbf{B}$ force, consistent with some escape of ions as they are scattered. A BBF can be spawned to interchange with its surroundings and result in weak injection at geosynchronous distance. Tailward in the disruption region ions left behind enhance the energetic-particle population of flux tubes and retard their earthward convective transport. Since the background current sheet is thicker further out, the CFCI is quenched, and the growth phase continues. With this constraint, the CFCI should merely result in thickening the current sheet in the central portion of the disruption region. This description is consistent with the pseudobreakup observations of *Koskinen et al.* [1993] and *Ohtani et al.* [1993].

Mathematical consideration of the CFCI in non-local approximation, i.e., including the background plasma and field gradients, leads to consideration of the lower-hybrid drift instability (LHDI) [*Lui*, 1992]. The LHDI is stabilized by high plasma β [*Huba and Papadopoulos*, 1978]. Current sheet thinning is driving the CFCI, and the so-called "driven" LHDI has been considered by *Papadopoulos et al.* [1990]. Their results show that if the current sheet thins fast enough, say with substorm-sized electric fields, the central plasma sheet can be unstable to the driven LHDI; growth times are long if only growth-phase sized electric fields are present. Recently, *Chang et al.* [1994] reported first results from their non-local analysis of the CFCI. Using mid-tail parameters [see *Lui*, 1992], they find the tail is stable against the CFCI. Lui warns that a more comprehensive sampling of the plasma and field parameter space is needed before any conclusion can be drawn.

We suspect that the CFCI provides stability of the current sheet against significant ion demagnetization during normal growth-phase thinning as described above. Thin current sheets, with thicknesses comparable to typical ion gyroradii, are commonly observed in the near-Earth plasma sheet, in some instances for tens of minutes, prior to substorm onset [e.g., *Pulkkinen et al.*, 1992]. During SMCs such thin current sheets can persist for hours before a change in solar-wind conditions results in substorm onset, marking the end of the SMC. (See, e.g., *Sergeev et al.* [1993].) These persistent thin current sheets tend to belie the notion that current disruption or tearing trigger substorm onset. However, the current disruption mechanism, when considered non-locally and in conjunction with tearing, is quite a complex problem. Much more analysis is needed before its role as an onset triggering mechanism can be determined.

Motivated by detailed particle and field observations at geosynchronous orbit, *Roux et al.* [1991] suggest the ballooning instability as the mechanism for substorm onset. Several talks at the ICS-2 meeting held in Fairbanks were supportive of some sort of ballooning scenario for substorm onset. Like the other proposed trigger mechanisms conventional ballooning is stabilized by compression of the plasma as flux tubes alter their volumes. Very special conditions are required if conventional ballooning is to be unstable in the near-Earth plasma sheet. Whether or not such conditions exist is an issue of active debate [e.g., *Pu et al.*, 1992; *Ohtani and Tamao*, 1993; *Lee and Wolf*, 1992]. In the next section we argue for a modified ballooning scenario as the triggering mechanism for substorm expansion onset. In this scenario, compressional stabilization is nullified by mass exchange between ionosphere and magnetosphere.

A Modified Ballooning Trigger for Substorm Onset

In our MHD stability analysis [*Erickson and Heinemann*, 1992 – paper 2], mass exchange between ionosphere and magnetosphere permits the isobaric modes. The mode in which near-Earth flux tubes contract earthward at constant pressure, requiring that ions flow down into the ionosphere, corresponds to the "ideal tearing mode" description of *Birn et al.* [1993]. The mode in which near-Earth flux tubes expand tailward at constant pressure, requiring that ions flow upward from the ionosphere, corresponds to the "protoplasmoid" or "global ballooning" description in paper 2. Certainly, plasma-sheet flux tubes can convect earthward just as fast as their ions can precipitate, but this is not what is observed. Quite the opposite is observed; ions of ionospheric origin are observed in the plasma sheet correlated with magnetospheric activity.

Within the context of M-I coupled convection and the MHD stability results, a promising scenario for triggering substorm onset unfolds. A portion of the upward Harang field-aligned current system will exist just poleward (tailward) of the duskside region-2 currents (i.e., the equatorward side of the Harang electric field reversal). This upward current could be particularly intense in association with the braking of earthward plasma-sheet flow and its westward acceleration in the inner-edge region near midnight. Associated with the upward currents can be upward potential drops and upward flows of ionospheric ions. In paper 2 we show that observed potential drops and upward ion fluxes are adequate to allow near-Earth flux tubes to expand tailward at constant pressure. A $1 R_E$ tailward displacement requires about a 2% increase in the energy content of a near-Earth plasma-sheet flux tube. This energy is comparable to the loss of flow energy during braking of 30 km/s earthward flow. So, it appears that "global ballooning" is feasible. As the upward currents increase late in the growth phase, they might exceed the rate in which electrons are scattered into the loss cone. A parallel electric field will be required to open the equatorial loss cone. The ion distribution and its pressure will shift toward the equator. Assuming a Maxwellian, $P_i \sim \exp[e\phi/kT_i]$. For an ionosphere-to-equator potential drop comparable to the electron thermal energy per charge, and $T_i/T_e \approx 7$, an approximate 15% equatorial shift in the pressure distribution along the field line will occur. For the stretched flux tubes late in the growth phase, the equatorial displacement is substantially a tailward displacement. (The pressure gradient scalelength in the near-Earth plasma sheet should be several R_E at this time.)

The destabilization of the fundamental, inward/outward, normal-mode oscillation of plasma-sheet flux tubes can be viewed in the following manner. As growth-phase stretching of the tail proceeds, the transition region between dipolar and taillike flux tubes in the inner-edge region of the plasma sheet shortens. The gradient in flux-tube volume in this transition region steepens, intensifying the differential gradient/curvature drift of charge species, and requires the intensity of upward (Harang) field-aligned current into the region to increase. Also, as the transition region narrows, the deceleration of earthward plasma flow and azimuthal acceleration increase, which might require field-aligned closure of inertial-driven currents. The development of potential drops will accelerate ionospheric ions into these braking flux tubes and cause the pressure along the flux tubes to shift toward the equator. This pressure redistribution can cause the equatorial, normal-mode oscillating electric field to overshoot the background convection electric field (reversing the electric field) as the equatorial ends of flux tubes displace tailward.

While this occurs, the lobe magnetic pressure is essentially unperturbed. Since the pressure gradient is earthward, tailward displacement of the equatorial pressure profile results in $P_{lobe} > P_{eq}$ near the inner edge, and $P_{lobe} < P_{eq}$ tailward of the inner edge. If the pressure displacement occurs over too-limited a radial extent, flux tubes on either side will be over- and under-compressed, and the mode will be stabilized. If however, pressure displacement occurs over a radial extent comparable to the plasma-sheet thickness, then the vertical pressure imbalance can be communicated to the lobes before the radial compressional mode can provide stabilization. This results in the out-of-equilibrium "protoplasmoid" or "global ballooning" picture of paper 2. Collapse ensues. Dipolarization occurs on the earthward side of the collapse; forced thinning of the plasma sheet occurs as the collapse travels downtail causing "neutral sheet" formation. The global ballooning triggers the end of the quasi-static growth phase and start of a dynamic phase. In this dynamic phase forced thinning of the current sheet can drive the CFCI mechanisms and tearing leading to X-line formation.

Various observations are supportive of this scenario. *Daglis et al.* [1993] show that the contribution to near-Earth plasma-sheet pressure from ionospheric ions correlates well with AU and poorly with AL during the growth phase. The near-Earth portion of the upward Harang currents westward and earthward of the Harang electric field reversal should close via the eastward electrojet (AU). (Note that M-I coupling was included in the MHD simulations by *Hesse and Birn* [1991], however, the runs did not include mass exchange with the ionosphere which could affect ion distributions along field lines.) The azimuthal periodicity in auroral luminosity prior to onset noted by *Elphinstone et al.* [1993] could be indicative of azimuthal structure of ballooning as discussed by *Roux et al.* [1991]. Global ballooning might be analogous to coronal mass ejections (CMEs) and flares. The CME (global ballooning?) is observed to precede the occurrence of the flare (indicative of reconnection) [e.g., *Kahler*, 1992; *Webb*, 1991]. Similarly, ballooning might explain the observations of *Lyons and Huang* [1992] who find plasma-sheet expansion at $\sim 20 R_E$ commencing as ground onset is recorded. SMCs do not provide for an *increasing* upward Harang current system and potential drops to provide for fast pressure redistribution on flux tubes, and hence, flux tubes cannot displace tailward at constant pressure, and onset is not triggered.

Summary

Consideration of the pressure-balance-inconsistency problem and MHD stability analysis of the magnetospheric configuration suggests that reconnection relatively near Earth is the operative mechanism of substorm expansion. What triggers onset of substorm expansion is less clear. Both theoretical and observational difficulties exist for the view that M-I coupling, conventional ballooning, current disruption, or tearing alone can trigger onset. We suggest a modified ballooning scenario, involving a critical role for M-I coupling of convection in the stability of the magnetospheric configuration, as a mechanism for triggering onset of the substorm expansion phase. In this scenario, upward acceleration of ionospheric ions and tailward pressure displacement, in association with upward field-aligned current (precipitating electrons) driven by convection during the growth phase, can destabilize the fundamental, inward/outward, normal-mode oscillation of plasma-sheet flux tubes. Observed upward ion fluxes and potential drops are adequate to allow outward displacement of near-Earth flux tubes sufficient to put the near-Earth plasma sheet out of quasi-static force balance with the lobes. This induces a dynamic phase whereby lobe collapse forcibly thins the current sheet wherein mechanisms such as current disruption and tearing can be effective in X-line formation near Earth.

Acknowledgments This work was supported by NASA under grants NAGW-2627 and NAGW-2856 and by the U.S. Air Force under contract F19628-90-K-0003 and its Office of Scientific Research under task 2311G5.

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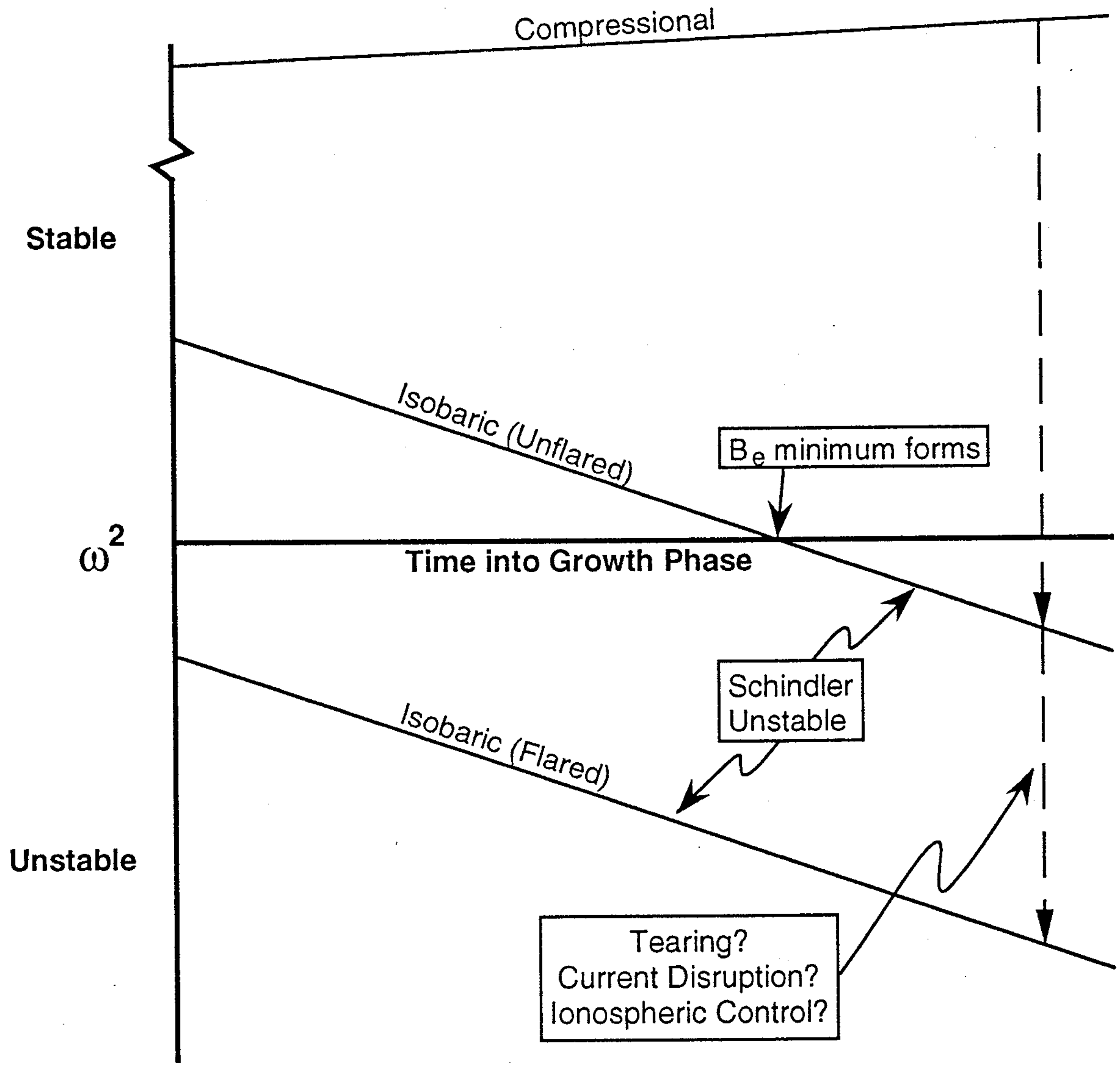

Figure 1. Summary illustration depicting the results of MHD stability analysis of self-consistent magnetospheric convection sequences. The square of the eigenfrequency of the fundamental normal mode ω^2 is plotted versus time into a convection sequence representative of a substorm growth phase. The fundamental normal mode is the inward/outward oscillation of plasma-sheet flux tubes. The magnetosphere is stable to compressional fluctuations, whereas the magnetosphere can be unstable to isobaric fluctuations. During a growth phase the magnetosphere evolves along the stable compressional branch. An outstanding problem is identification of the mechanism which triggers the transition from the stable to unstable branch, marking the end of a growth phase and substorm onset.